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16. ABSTRACT

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considerable variability, both in tree size and in ultimate yield of trees on clonal as well as seedling stocks.

Literature Cited

1. Cameron, H. R., M. N. Westwood, and P. B. Lombard. 1969. Resistance of Pyrus species and cultivars to *Erwinia amylovora*. *Phytopathology* 59:1813-1815.
2. Reimer, F. C. 1950. Development of blight resistant French pear rootstocks. *Ore. Agr. Expt. Sta. Bul.* 485.
3. Westwood, M. N., and P. B. Lombard. 1966. Pear rootstocks. *Ore. Hort. Soc. Annu. Rpt.* 58:61-63.
4. _____and A. N. Roberts. 1970. The relationship between trunk cross-sectional area and weight of fruit trees with special reference to the apple. *J. Amer. Soc. Hort. Sci.* 95:28-30.
5. _____and P. H. Westigard. 1969. Degree of resistance among pear species to the woolly pear aphid *Eriosoma pyricola*. *Proc. Amer. Soc. Hort. Sci.* 94:91-93.
6. _____, F. C. Reimer, and V. L. Quackenbush. 1963. Long-term yields as related to ultimate tree size of three pear varieties on five *Pyrus* rootstocks. *Proc. Amer. Soc. Hort. Sci.* 82:103-108.
7. _____, H. R. Cameron, P. B. Lombard, and C. B. Cordy. 1971. Effects of trunk and rootstock on decline, growth and performance of pear. *J. Amer. Soc. Hort. Sci.* 96:147-150.

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Radiation Environment of Growth Chambers[1]

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Additional index words. controlled environments, light, illumination, measurement.

Abstract. **Radiation measurements with different types of meters in several controlled environment facilities have been compiled to demonstrate the problems associated with insuring uniform radiation levels in separate facilities. Data are provided for a quantum meter, three photometers, a pyranometer and a far-red energy meter. Significant variations in total radiant energy in chambers under similar photosynthetically active radiation (PAR) levels were demonstrated. Measurement of light under cool white fluorescent and incandescent lighting with calibrated photometers from different manufacturers, varied by 20%. Greater variation occurred when photometer measurements were compared under different types of lamps. One of the most significant variations in different chambers was the intensity of incandescent radiation. This could only be effectively monitored and controlled with the far-red sensor. Factors are given for conversion between quantum, photometric and radiometric measurements, but high precision cannot be assumed in the use of these factors because of the differences in instrument sensitivity and variations in spectral output of lamps. The study documents the need for calibration of instruments under the same type of light source that is utilized in the growth chambers and for the use of more than one type of sensing instrument to quantify the radiation that controls plant growth.**

The Growth Chamber Committee of the American Society for Horticultural Science has undertaken a project to improve uniformity and comparability in growth chamber research (2). As part of their efforts they have obtained funding from the National Science Foundation to purchase a group of environmental sensing instruments that are exchanged among committee members to facilitate uniformity in environmental monitoring (1). These instruments include 6 different radiation sensing meters. During the course of studies with these instruments over the past 2 years considerable radiation data have been obtained. These data provide information on the magnitude of measured differences in radiation that have been found in different laboratories in plant growth chambers having similar lamp sources and demonstrate the difficulties associated with insuring uniformity in measurement and establishment of radiation levels in controlled chambers. Measurement difficulties that have been recognized and documented by several workers (9, 10, 11, 12, 14, 16, 21, 22) have led to detailed characterization of the radiation environment (3, 5, 6, 7) and recommendations for procedures to minimize the problems (2, 8, 20, 21). Recently, McCree (15, 17) provided a large amount of data to document the usefulness of quantum measuring instruments that were developed (4, 19) for accurately monitoring the radiation that is utilized for photosynthesis by the plant. This report compares measurements with a quantum meter, pyranometer, far-red irradiance meter and three photometers in the separate laboratories.

Materials and Methods

The following radiation sensing instruments[11] were in the NSF instrument package. Data collected from these sensors form the basis of the report.

Photometer, Weston – Selenium sensor without cosine correction and not corrected for eye sensitivity. Model 756 Sun-

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[11]Mention of a trademark name or a proprietary product does not imply it's approval by the EPA, USDA, or other institutions to the exclusion of other products that may also be available.

light illumination meter, Weston Instrument Company.

Photometer, Gossen – Silicon sensor with cosine correction and filters to provide measurement of radiation corrected for eye sensitivity. Model 130-063, Gossen Instrument Company.

Photometer, Lambda – Silicon sensor with cosine correction and filters to correct for eye sensitivity. Model LI-210S, Lambda Instrument Company.

Pyranometer, Eppley – Differential thermopile sensor with temperature correction and cosine correction. Sensitivity between 280–2800 nm. Model 8-48, Eppley Laboratory, Inc.

Quantum Meter, Lambda – Silicon sensor with interference filters and cosine correction to provide quantum flux measurements. Sensitivity between 400 and 700 nm. Model LI-190S, Lambda Instrument Company.

Far-red Meter, Lambda – Silicon sensor with cosine correction and narrow band filters. Sensitivity with peak at 763 nm and half-band width of 87 nm, Lambda Instrument Company.

The waveband sensitivity curves for each sensor as provided by the manufacturer are shown in Fig. 1, 2 and 3.

All light sensors were compared with each other under a carbon arc lamp (Pyrometric Molarc Lamp Type 2371, Mole-Richardson Co.), established as the standard radiation source for this study. This was utilized because it provided a reproducible illuminance up to 21.50 klx (2000 ft-c). It was fitted on an optical bench to position sensors precisely in order to achieve a known uniform illuminance over a surface slightly larger than the area of the largest sensor. Illuminance and irradiance values produced by the lamp were calculated from published values of the spectral radiance of the positive electrode of the arc when operated under specified conditions. These calculated values are believed to be correct to within 2% and are referred to hereafter as the "known" values. No detectable sensor fatigue was found in repeated calibrations by each of the meters with the carbon arc source in the two year period of this study, therefore, no electronic or mechanical adjustments were made to any of the radiation meters during this period. The SD for each meter with this light source was less than 3%. Table 1 shows the irradiance/illuminance by the carbon arc source as indicated by each of the above instruments along with the known values of the irradiance/illuminance, based upon assuming an ideal response for each meter; eye sensitivity for photometers, number of photons in 400–700 nm wavelengths for quantum meters, and radiant power (radiant energy per unit time) in 720–850 nm wavelengths for the far-red meter. No calculation of irradiance was made for the pyranometer because of uncertanties in the spectral irradiance of the carbon arc source at wavelengths above 1000 nm. At the 21.50 klx illuminance position on the optical table, the irradiances/illuminances indicated by the Weston photometer, Lambda quantum meter, far-red meter, and pyranometer were close to the known value. However, the irradiance indicated by the Gossen meter was 11% lower and the indication by the Lambda photometer was 9% higher than the known level. Thus these deviations from known values have been applied as a correction to all readings taken in the different laboratories by these two instruments.

In addition to this calculated adjustment and to illustrate

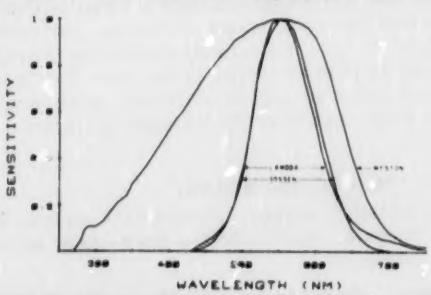

Fig. 1. Wavelength response of Gossen, Lambda and Weston photometers.

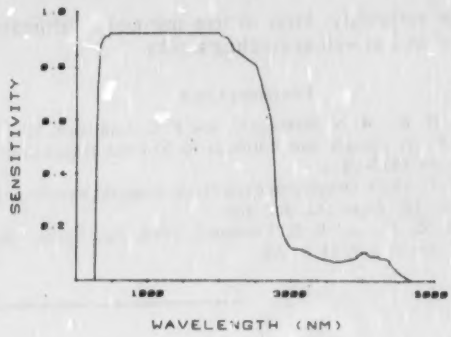

Fig. 2. Wavelength response of Eppley pyranometer.

both the differences encountered and some of the potential problems incurred in controlled environment studies it was necessary to normalize the data to a common set of irradiation conditions. This was done by simply scaling the observed irradiation levels up or down, as long as the instrument indications were linearly related to the irradiance of the sensor (Table 2). The linearity of the instruments was checked over the illuminance range of 5.38 to 21.50 klx on the optical bench and no significant deviations were found. (Some error will be introduced when irradiation under a particular source deviates greatly from this normalized value because of inaccuracies in scale readings at extreme values.) The quantum flux readings were selected as the basis for this normalization of irradiation levels because they represent a measurement of radiation that is most directly proportional to the rate of photosynthesis by a plant. This radiation is referred to as photosynthetically active radiation (PAR). The selected value of 325 micro Einsteins (μE) $m^{-2}sec^{-1}$ with this meter, required a minimum correction to provide normalization of readings from all instruments under all observed conditions of irradiation.

The sunlight readings were taken at noon on a clear day; the sun was at an angle of 53° from the vertical with the meters directed vertically.

Specifications for the growth rooms or growth chambers in the separate laboratories in which these measurements were made are indicated in Table 3.

Results

Radiation measurements in different laboratories under similar radiation sources. Radiation measurements were taken with the above instruments in twelve laboratories in the United States, Canada, and the Netherlands.

Despite differences in growth chamber design, measurements with the quantum meter and photometers resulted in comparable readings where the same radiation sources of cool white fluorescent and incandescent light were used. The SD for the readings with the Weston, Gossen, and Lambda photometers in the separate chambers were 0.86, 1.01 and 0.62 klx respectively with a maximum difference of 14%, 13% and 9% respectively

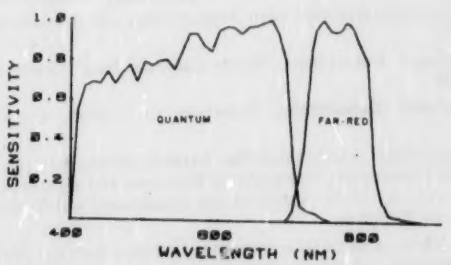

Fig. 3. Wavelength response of Lambda quantum and far-red meters.

Table 1. Calibration of radiation meters utilized by ASHS Growth Chamber Committee from 1972-1974.

Meter (manufacturer)	Irradiance/illuminance level indicated by meter (carbon arc source[z])	Irradiance/illuminance level calculated for carbon arc source	Correction factor for indicated level
Quantum (Lambda)	406 ± 5 μE $m^{-2}sec^{-1}$	403 μE m^{-2} sec^{-1}	None
Photometer (Weston)	21.75 ± 0.51 klx (2023 ft-c)	21.50 klx	None
Photometer (Gossen)	19.08 ± 0.56 klx (1775 ft-c)	21.50 klx	1.127
Photometer (Lambda)	23.38 ± 0.48 klx (2175 ft-c)	21.50 klx	0.920
Pyranometer (Eppley)	296 ± 6 Wm^{-2}	Not determined	None
Far-red (Lambda)	0.185 ± 0.001 $Wm^{-2}nm^{-1}$	0.189 $Wm^{-2}nm^{-1}$	None

[z]Values represent the arithmetic mean of 20+ measurements made over a 2 year period, ±SD.
Units:
$\mu Em^{-2}sec^{-1}$ = micro Einsteins $meter^{-2}sec^{-1}$
klx = 1000 lux
Wm^{-2} = Watts x $meter^{-2}$
ft-c = foot candles
nm = nanometers

based on the average illuminance measured with each of these three meters (Table 2). This variation is greater than the SD obtained for the several readings taken under the carbon arc source with the Weston, Gossen and Lambda photometers of 0.51, 0.56 and 0.48 klx, respectively (Table 1). The Weston meter generally indicated lower radiation values than the Gossen photometer or the Lambda photometer under this combination of cool white fluorescent and incandescent lamps.

Pyranometer readings varied greatly in the different chambers. This would result from large differences in incandescent radiation in the different chambers. The power output (wattage) of incandescent lamps varied significantly in the different

Table 2. Comparison of irradiance/illuminance measurements taken in chambers of different laboratories in the U. S., Canada and the Netherlands with the NSF instruments.

Laboratory	Manufacturer and type of chamber	Multiplier[z]	Quantum Meter Lambda ($\mu Em^{-2}sec^{-1}$)	Photometers: Weston (klx)[y]	Photometers: Gossen (klx)	Photometers: Lambda (klx)	Pyranometer Eppley (Wm^{-2})	Far-red sensor Lambda ($Wm^{-2}nm^{-1}$)
Post Laboratory Ithaca, NY	EGC Walk-in Custom made	0.99	325	23.29	27.46	21.74	138	0.079
Phytotron Raleigh, NC	EGC Reach-in Model M-3	1.00	325	21.06	26.90	22.93	173	0.116
Phytotron Durham, NC	EGC Walk-in Custom made	1.18	325	20.92	25.74	--	153	0.084
Plant Stress Lab Beltsville, MD	EGC Reach-in Model M-13	0.79	325	21.29	25.94	21.81	197	0.112
Environmental Labs Las Vegas, NV	EGC Reach-in Model M-3	0.98	325	22.76	27.46	21.74	176	0.083
Horticultural Labs Madison, WI	EGC Reach-in Model M-3	1.09	325	22.11	27.47	21.03	138	0.071
Biotron Madison, WI	Built-in rooms	0.94	325	21.04	26.93	21.31	129	0.078
Agronomy Labs Madison, WI	Percival Walk-in Model PGW-108	1.06	325	21.32	26.60	22.69	71	0.043
Horticultural Labs Lafayette, IN	Warren-Sherer Reach-in Model CEL-512-37	0.93	325	20.99	24.79	22.23	116	0.052
Horticultural Labs Guelph, Ont. Can.	Cont. Environ. Reach-in Model E-15	0.94	325	20.18	--	21.23	156	0.082
Plant Phys. Labs. Ond. Wageningen, Neth.	Built-in rooms	1.00	325	20.96	--	21.23	118	0.079
Los Angeles Arboretum Los Angeles, CA	Warren-Sherer Reach-in Model CEL-8	1.02	325	21.53	28.20	21.48	174	0.068
Average ± SD		0.99 ±0.10		21.45 ±0.86	26.75 ±1.01	21.77 ±0.62	145 ±34	0.079 ±0.021

[z]The radiation levels in the various chambers were normalized in such a way that the Quantum Meter would have indicated the same irradiance in all chambers. Multiplier is value that readings with each meter were multiplied by to obtain equal quantum flux density values for each chamber.

[y]klx x 93.02 = ft-c

Table 3. Chamber specifications for various reach-in and walk-in chambers used by the ASHS Growth Chamber Committee members.

Laboratory	Chamber manufacturer and type	Interior area (m^2)	Distance from lamps (m)	Barrier material	Reflective surfaces	Lamp type	Lamp amperage or voltage	Total wattage (assume 120 V line)	Lamp wattage per m^2 of growing area
Post Laboratories Ithaca, NY	Environmental Growth Chambers Walk-in Custom	9.0	1.35	Plexiglass	aluminized mylar	cool white fluorescent	1500 mA	9460	1050
						Incandescent	130 V	2520	280
Phytotron Raleigh, NC	Environmental Growth Chambers Walk-in Custom	9.7	1.35	Plexiglass	specular aluminin	cool white fluorescent	1500 mA	18060	2005
						incandescent	130 V	4600	510
Phytotron Raleigh, NC	Environmental Growth Chambers Reach-in M-3	1.08	.60	Plexiglass	specular aluminin	cool white fluorescent (power groove)	1500 mA	1200	1600
						incandescent	130 V	600	800
Phytotron Durham, NC	Environmental Growth Chambers Walk-in Custom	3.0	2.28	Plexiglass	specular aluminum	cool white fluorescent	1500 mA	3870	1290
						incandescent	130 V	1200	400
Plant Stress Laboratory Beltsville, MD	Environmental Growth Chambers Reach-in M-13	0.75	0.56	Plexiglass	specular aluminum	cool white fluorescent	1500 mA	1600	2133
						incandescent	130 V	800	1067
Environmental Laboratory Las Vegas, NV	Environmental Growth Chambers M-3 Reach-in	0.75	0.75	Plexiglass	polished stainless steel	cool white fluorescent	1500 mA	2200	2933
						incandescent	130 V	450	600
Horticultural Laboratory Madison, WI	Environmental Growth Chambers M-3 Reach-in	0.75	0.63	Plexiglass	aluminized mylar	cool white fluorescent	1500 mA	2000	2700
						incandescent	120 V	240	320
Biotron Madison, WI	Built-in Rooms	7.2	1.0	Plexiglass	white-pigmented fiberglass	cool white	1500 mA	17200	2389
						incandescent	Variable		
Agronomy Labs Madison, WI	Percival Walk-in PGW-108	3.0	1.12	Diffusing fiberglass	white enamel	cool white fluorescent	1500 mA	6020	2007
						incandescent	120 V	120	40
Horticultural Labs Lafayette, IN	Warren-Sherer CEL 512-37 Reach-in	3.5	0.80	None	white enamel	cool white fluorescent	1500 mA	3450	1045
						incandescent	120 V	720	218
Horticultural Labs Guelph, Ontario	Controlled Environments E-15 Reach-in	1.42		None	white enamel	cool white fluorescent	1500 mA	2640	1859
						incandescent	120 V	720	507
Plant Physiol Laboratory Ond Wageningen Netherlands	Built-in Rooms	1.76	0.90	Plexiglass	white paint	cool white fluorescent	1500 mA	3120	1773
						incandescent	220 V	1100	625
Los Angeles Arboretum Los Angeles CA	Warren-Sherer CEL-8 Reach-in	0.72	0.34	None	aluminized mylar	cool white fluorescent	1500 mA	1100	1528
						incandescent	120 V	200	278

chambers (Table 3) because of differences in voltage rating of the lamps. Additional variation in power output likely occurred because of undetermined differences in line voltage. The significance of lamp voltage and line voltage to lamp output is discussed by Downs (9).

The level of far-red radiation indicated by the Lambda far-red sensor also varied greatly in the different chambers (Table 2). Again, this resulted from differences in the amount of incandescent light and the corresponding long wave radiation in each chamber. Although these readings followed the same trend as the pyranometer readings, the ratio of far-red to pyranometer radiation varied greatly in the different chambers. Therefore, separate measurements are required to determine the actual amount of far-red radiation incident on the plants.

Radiation measurements under different radiation sources. Six sensors were evaluated under different types of radiation sources (Table 4). Readings were normalized to quantum meter readings of 325 $\mu E\ m^{-2}sec^{-1}$.

A comparison of the meter indications for the three photometers reveals that spectral sensitivities of these meters were quite different. These differences were as much as 30% as shown by the comparison of photometric readings under an HID lamp and sunlight. With the Weston photometer, a reading was obtained under HID sodium vapor lamps that was 15% less than under sunlight, while for the Lambda photometer the relationship was almost exactly reversed. The photometer readings for the mercury vapor and metal halide lamp sources were high compared to readings under other lamp sources in these norma-

Table 4. Comparison of radiation meter readings under different radiation sources.

Radiation and lamp type	Multiplier[z]	Quantum meter Lambda ($\mu E\ m^{-2}\ sec^{-1}$)	Photometer			Pyranometer Eppley (Wm^{-2})	Far-red meter Lambda ($Wm^{-2}nm^{-1}$)
			Weston (klx)[y]	Gossen (klx)	Lambda (klx)		
Low pressure fluorescent							
Cool white (1500 mA)	1.14	325	22.05	26.52	21.59	70	0.016
Warm white (1500 mA)	0.85	325	21.06	24.80	21.56	55	0.014
High pressure discharge (HID)							
Mercury vapor (400 W)	1.00	325	25.25	29.07	22.98	155	0.038
Metal Halide (400 W)	1.00	325	24.72	25.92	22.12	218	0.050
Sodium vapor (400 W)	1.00	325	18.27	22.78	19.86	118	0.091
Other Sources							
Incandescent (150 W)	6.99	325	15.77	17.94	12.98	578	0.565
Carbon arc	0.80	325	17.20	17.20	17.20	240	0.146
Sunlight	0.27	325	21.62	22.92	16.09	150	0.187

[z]The radiation levels in the various chambers were normalized in such a way that the Quantum Meter would have indicated the same irradiance in all chambers. Multiplier is value that readings with each meter were multiplied by to standardize PAR meter readings to 325 $\mu E\ m^{-2}sec^{-1}$.

[y]klx x 93.02 = ft-c

lized data, because these lamps produce maximum radiation near the center of the visible spectrum. The pyranometer and far-red meter readings were high for incandescent and carbon-arc radiation sources both of which have peak radiation at a wavelength longer than 700 nm.

Measurements were also made with the different instruments in one laboratory under the combination of fluorescent and incandescent light and then separately under the same sources. Readings were first taken under the combined sources and then the incandescent lamps turned off to obtain radiation levels under the cool white fluorescent lamps alone. Then the converse was done after a 15 minute period to assure lamp equilibration. As is to be expected from any light meter for which the output indication is directly proportional to the radiation input, the sum of the radiation levels measured under the separate light sources very nearly equaled the readings obtained under the combined sources (Table 5); this was irrespective of the meters utilized, and these results illustrate the contribution of each light source to both photosynthetic radiation and total radiant energy.

Comparison of quantum meter indication to photometer and pyranometer measurements under different radiation sources. The quantum flux (PAR) readings under different radiation sources were compared to the photometer and pyranometer readings and conversion values calculated (Table 6). The photometer comparisons vary from 25 $\mu E\ m^{-2}sec^{-1}$ per klx for incandescent sources to 14 $\mu E\ m^{-2}sec^{-1}$ per klx for HID mercury vapor sources for upper range klx values. Light sources having a small percentage of photosynthetically active radiation close to the maximum sensitivity of photometers at the 550 nm wavelength, had the largest PAR values.

The pyranometer comparisons to PAR varied as much as 10 fold for the different light sources. A maximum value of 6.0 PAR for each Wm^{-2} for warm white fluorescent light and a minimum value of 0.6 PAR for each Wm^{-2} for the incandescent source was found. Large PAR values for each

Table 5. Comparison of radiation measurements taken with different instruments under cool white fluorescent and incandescent light alone and combined.

Lamp type[z]	Quantum meter Lambda ($\mu E\ m^{-2}sec^{-1}$)	Photometers			Pyranometer Fppley (Wm^{-2})	Far-red meter ($Wm^{-2}nm^{-1}$)
		Weston (kox)[y]	Gossen (klx)	Lambda (klx)		
Fluorescent alone (measured)	285.0	19.35	20.64	20.60	67.2	0.016
Incandescent alone (measured)	46.5	2.26	2.28	2.02	81.6	0.082
Fluorescent plus incandescent (summed)	331.5	21.61	22.92	22.62	148.8	0.098
Fluorescent plus incandescent (measured)	327.0	21.77	22.58	23.20	144.5	0.096

[z]Rated wattage – 3660 W cool white fluorescent and 750 W incandescent.

[y]klx x 93.02 = ft-c.

Table 6. Conversion values for photometric and radiometric measurements to PAR ($\mu E\ m^{-2}sec^{-1}$) measurements under different radiation sources.

Radiation and lamp type	PAR/klx[z]	PAR/Wm^{-2} (280–2800 nm)[y]	PAR/$Wm^{-2}nm^{-1}$ (720–800 nm)[x]
Low pressure fluorescent			
Cool white (1500 mA)	12.25–15.05 (0.13–0.16)	4.71	2.03×10^4
Warm white (1500 mA)	13.10–15.43 (0.14–0.17)	6.02	2.32×10^4
High pressure discharge (HID)			
Mercury vapor (400 W)	11.18–14.14 (0.12–0.15)	2.12	8.33×10^4
Metal halide (400 W)	12.54–14.69 (0.14–0.16)	1.51	6.37×10^4
Sodium vapor (400 W)	14.27–17.79 (0.15–0.19)	2.80	3.53×10^3
Other sources			
Incandescent (150 W)	18.12–25.04 (0.20–0.27)	0.57	5.66×10^3
Carbon arc	18.90 (0.20)	2.20	1.71×10^3
Sunlight	14.18–20.20 (0.15–0.22)	1.37	2.20×10^3

[z]As determined with the three photometers. Maximum and minimum values indicated. PAR/ft-c in parenthesis.

[y]As determined with Eppley pyranometer.

[x]As determined with Lambda far-red meter.

Wm^{-2} were obtained for those sources with all or most of the emitted radiant energy in the photosynthetically active region of the spectrum (between 400 and 700 nm) and small PAR values for those with a small percentage in this region. The comparisons for PAR values to far-red meter readings (sensitive to wavelengths from 720–800 nm) under different radiation sources were quite different from comparisons for PAR values to pyranometer values.

Discussion

These data demonstrate the typical variation in radiation level that can be expected for growth studies conducted at different or the same laboratories where different indicating meters are used. This variation occurs because the spectral response of different meters is not the same. The ideal indicated response is rarely achieved; i.e., photometric, quantum or radiant energy for it is very difficult to produce filters that will provide the precise spectral sensitivity as indicated for the meter. This variation is intensified when comparing light sources that have sharp peak emissions at certain wavelengths as with fluorescent and high intensity discharge lamps (3, 6). This variation could be minimized if meter calibrations were carried out under the radiation source utilized for experimentation. Presently most calibrations are made under incandescent lamps at a specified color temperature. The spectrum of this radiation source is very different from that of the fluorescent or HID lamps under which most plant experiments are conducted. One manufacturer of sensors for plant studies makes an initial standardization under quartz halogen standard lamps and a check under cool white fluorescent lamps. Precision in this second calibration is limited by the lack of satisfactory primary standards for fluorescent lamps. Most manufacturers, however, make no attempt to calibrate sensors under lamp sources other than tungsten lamps, so significant variation in growth chamber light measurement can be anticipated.

The variation in spectral sensitivity of meters will be an even greater problem when comparing experiments conducted under lighting that is provided by a mixture of two different types of lamps such as fluorescent and incandescent. Unless the ratio of irradiance from the two lamp types is the same in each laboratory, and calibration is carried out under both lamps at this relative ratio, satisfactory precision cannot be expected. This error is minimized for plant research when meters are calibrated against the lamp type that is providing the majority of the photosynthetic radiation in the chamber.

Certain radiation meters were developed for use with a radiation source having a specific relative spectral distribution and will not produce accurate measurements under other radiation sources. These limited-use instruments are not filtered to provide the desired response but only calibrated under the specific radiation source for which they are recommended. For example, the Weston, Model 756, sunlight illumination meter that indicates ft-c is not filtered to produce the ideal ft-c response (Fig. 1) and will only provide accurate measurements under sunlight or a source with a relative spectral distribution similar to sunlight. The distribution of these limited-use instruments to biologists, without adequate precautionary statements on the meters has contributed significantly to inaccuracies in controlled environment radiation measurements.

The conversion values as provided in Table 6 for radiation meters utilized under different lamp types cannot be considered as absolute values and will deviate significantly from readings taken with different meters. This can be seen by comparing these results to conversion values previously reported (9, 12, 16).

Variation in radiation measurement of the magnitude reported in this study have been recognized and reported by scientists familiar with the construction and characteristics of radiation indicating instruments (17, 22). However, biologists are often unaware of these inaccuracies and even if they were aware, it is very difficult for biologists or any scientists to establish the extent of the inaccuracies for light sources in controlled environments under which they are working. The inaccuracies could be minimized significantly if effective procedures were developed for the regular periodic calibration of instruments under the separate types of light sources being utilized by biologists in controlled environments.

The commercial availability of instruments for measuring quanta or photons provides plant scientists with a measurement that is closely proportional to the capability of a radiation source to encourage photosynthesis in plants (15, 16). In contrast photometric and pyranometer measurements were developed for other purposes and they therefore cannot be directly related to the photosynthetic activity in plants. The photometer measurements provide an underestimate of the photosynthesis induced by blue and red wavelengths and an overestimate of that induced by green light. The pyranometer measurements provide a reasonably accurate estimate of the photosynthetic capacity of the fraction of radiation in the visible range but they also measure radiation beyond this range which has no photosynthetic significance. The use of "sharp-cut" color glass filtering on pyranometers or other radiometers to eliminate all radiation below 400 nm and above 700 nm greatly increases their usefulness for evaluating photosynthetic activity in growth chamber studies.

The need to characterize the level of red and far-red irradiance is of special importance for germination, morphogenesis, flowering and other phytochrome mediated responses of plants (18). Although only far-red measurements were made in these

studies, it would have been desirable to obtain separate measurements of irradiance for red and blue wavebands also.

The total radiant energy as monitored with the Eppley pyranometer provides necessary information for determining radiation effects upon soil and plant temperatures and establishing the total radiant energy released within the chamber. The total radiant energy cannot be effectively determined with photometers or quantum meter measurement, for these meters are not sensitive to the radiation in the far-red wavelengths that may constitute a significant proportion of the radiant energy of certain light sources.

No attempt has been made to compare the level of irradiance in different chambers so that the irradiance efficiency could be determined for different types of chamber designs, since no efforts were taken during these measurements to ensure that lamp output was uniform. Lamp output would not have been uniform in the separate chambers because there were no controls on lamp bulb temperature, tube preburning time, or distance from the lamps to the measurement position. All of these and several other uncontrolled factors can markedly influence the total illuminance or irradiance at the sensor positions.

Although numerous studies have been conducted attempting to quantify the response of plants to different intensities and wavelengths of artificial radiation sources, very few of these studies have ensured that the meters being utilized were providing relevant radiation measurements with the different types of lamps and mixed lamp sources being utilized. The results of this study reinforce the need for additional standardization in irradiation measurement for plant research; this would include the development of calibration lamps for each of the principal lamp types utilized in plant growth studies, along with the establishment of standardized calibration procedures on an international basis.

Literature Cited

1. Anonymous. 1973. ASHS Growth Chamber Committee awarded NSF grant. *HortScience* 8:231.
2. ASHS Committee on Growth Chamber Environments. 1972. Guidelines for reporting studies conducted in controlled environment chambers. *HortScience* 7:239.
3. Bickford, E. D. and S. Dunn. 1972. Lighting for plant growth. Kent State Univ. Press, Kent, Ohio.
4. Biggs, W. W., A. R. Edison, J. D. Eastin, K. W. Brown, J. W. Maranville, and M. D. Clegg. 1971. Photosynthesis light sensor and meter. *Ecology* 52:125-131.
5. de Bilderling, N. and Nguyen-duy-thank. 1971. L'eclairage des serres en France. *Lux* 64:337-350.
6. Campbell, L. E., R. W. Thimijan, and H. M. Cathey. 1975. Spectral radiant power of lamps used in horticulture. *Trans. Amer. Soc. Agr. Eng.* 18:952-956.
7. Carpenter, G. A. and L. J. Moulsley. 1960. The artificial illumination of environmental control chambers for plant growth. *J. Agr. Eng. Res.* 5:283-306.
8. Committee on Plant Irradiation of the "Nederlandse Stichting voor Verlichtingskunde". 1953. Specification of radiant flux and radiant flux density in irradiation of plants with artificial light. *J. Hort. Sci.* 28:177-184.
9. Downs, R. J. 1975. Controlled environments for plant research. Columbia University Press, New York.
10. Dunkle, R. V. 1963. Radiation in phytotrons. *In* Engineering aspects of environment control for plant growth. Proc. Symp. Sept. 1-5, 1962.
11. Gaastra, P. 1959. Photosynthesis of crop plants as influenced by light, carbon dioxide, temperature and stomatal diffusion resistance. *Meded. Landbouwh. Wageningen* 59:1-68.
12. Hammer, P. A. and R. W. Langhans. 1972. Experimental design considerations for growth chamber studies. *HortScience* 7:481-483.
13. Kalbfleisch, W. 1963. Artificial light for plant growth. p. 159-174. *In* Engineering aspects of environment control for plant growth. Proc. Symp. September 1-5, 1962. CSIRO, Melbourne, Australia.
14. Klein, R. 1973. Determining radiant energy in different wavelengths present in white light. *HortScience* 8:210-211.
15. McCree, K. J. 1972. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agr. Meteorol.* 9:191-216.
16. _____. 1972. Test of current definitions of photosynthetically active radiation against photosynthesis data. *Agr. Meteorol.* 10:443-453.
17. _____. 1973. The measurement of photosynthetically active radiation. *Solar Energy* 15:83-87.
18. Mitrakos, K. and W. Shropshire, Jr. 1972. Phytochrome. Proc. Symp. 1971. Eretria, Greece, Acad. Press, New York.
19. Norman, J. M., C. B. Tanner, and G. W. Thurtell. 1969. Photosynthetic light sensor for measurements in plant canopies. *Agron. J.* 61:840-843.
20. Norris, K. H. 1968. Evaluation of visible radiation for plant growth. *Annu. Rev. Plant Physiol.* 19:490-499.
21. Trickett, E. S., L. J. Moulsley, and R. I. Edwards. 1957. Measurement of solar and artificial radiation with particular reference to agriculture and horticulture. *J. Agr. Eng. Res.* 2:86-110.
22. Zaha, M. A. 1972. Shedding some needed light on optical measurements. *Electronics* 45(23):91-96.